METHOD AND DEVICE FOR OPTICAL NAVIGATION

Technical Field

This application relates to motion sensing devices and more particularly to

5   devices, systems and methods for using specular reflection images to determine

relative motion.

Background of the Invention

Optical relative motion detection devices typically utilize image correlation

10   techniques to determine relative motion between the navigation device and a surface

by capturing images of the surface as the navigation device passes over the surface or

as the surface moves past the navigation device. Both the displacement and the

direction of the relative motion of the navigation device with respect to the surface

are determined by comparing one image with the following image. Typically,

15   intensity variations due to shadows cast on the surface are detected and the sensitivity

and applicability of this technique depend on the intensity contrast in the captured

images. Relative motion navigation devices are used, for example, for computer

screen pointer (e.g. mouse) control.

U.S. Patent No. 5,786,804, 5,578,813, 5,644,139, 6,442,725, 6,281,882 and

20   6,433,780 disclose examples of optical mice, other hand-held navigation devices and

hand-held scanners. These patents are incorporated herein by reference.

Typical existing optical navigation devices use light emitting diodes (LEDs) to

obliquely illuminate the surface to be navigated. Height variations on the surface, on

the order of 5 to 500 μm, cast shadows described by geometrical ray optics. The size

25   and contrast of the shadow pattern images depends in part on the type of surface

through the size of the height variation. Typically, the detector is positioned to receive the reflection in the surface normal direction and the angle between the surface and the incident light is typically selected to optimize the contrast of the shadow pattern images as is familiar from dark field imaging. Typical values for the

5   angle of incidence are in the range from about 5 degrees to about 20 degrees.

Smooth surfaces such as whiteboard, high gloss paper, plastic or painted metal present functional challenges to typical current optical navigation devices. In general, smooth surfaces are those containing less mid spatial frequency and more high spatial frequency structures. To increase the signal level, high optical power is required for

10   LED illumination resulting in typical current draws in excess of 30 mA.

Summary of the Invention

In accordance with the invention, a preselected angular distribution of reflected light is captured by the detector of an optical navigation device. Typically,

15   the detector of the optical navigation device is positioned to capture the specular reflection from the surface. The specular reflection creates an image of the surface that differs from both shadow pattern images and speckle patterns. Specular reflection typically provides a better signal compared to the shadow pattern image approach. This allows high contrast images to be obtained even on extremely smooth surfaces.

20   Additionally, image quality is preserved with respect to Lambertian surfaces because light is still scattered into the specular direction. The specular reflection images depend on the wavelength of the illumination source; typically the contrast of the specular reflection images increases as the bandwidth of the illumination source decreases, therefore laser based illumination affords the highest contrast.

In accordance with the invention, power requirements may be reduced by using an illumination source whose wavelength lies at the peak of the detector responsivity curve. The contrast of the specular reflection images depends on the degrees of spatial and temporal coherence of the illumination source. Use of a narrow

5   band illumination source such as a vertical cavity surface emitting laser (VCSEL) or narrow band light emitting diode (LED) provides enhanced image contrast at reduced power. Increasing the bandwidth induces averaging resulting in lower contrast as the returns from individual scatterers illuminated at different wavelengths add incoherently. Therefore, in accordance with the invention, the bandwidth of the

10   illumination source must be narrow enough to have sufficient coherent interference to obtain images of sufficiently high contrast to for reliable optical navigation. For example, an illumination source having a bandwidth on the order of 20 nm provides sufficient contrast for optical navigation on a large range of surfaces in the office desktop environment.

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Brief Description of the Drawings

FIGs. 1a – 1c illustrate light reflection from different types of surfaces.

FIG. 1d illustrates the concept of scattering from a surface in accordance with the invention.

20   FIG. 2 illustrates specular reflection in accordance with the invention.

FIG. 3a shows a high level block diagram in accordance with the invention.

FIG. 3b shows a simplified illustration of optical components of an embodiment in accordance with the invention.

FIG. 4 shows a system in accordance with the invention.

25   FIG. 5 shows an embodiment in accordance with the invention.

FIG. 6 shows an embodiment in accordance with the invention.

FIG. 7 shows a flow diagram depicting steps involved in a method in accordance with the invention.

Detailed Description of the Invention

If a light beam is incident on a smooth surface, the light rays of the incident beam reflect and remain concentrated in a bundle upon leaving the smooth surface. However, if a surface is microscopically rough, then the light rays reflect and scatter in many different directions. The spatial frequency corresponding to the surface roughness may be on the scale of the illumination wavelength. Each individual ray follows the law of reflection. However, in the case of a rough surface each individual ray meets a portion of the surface that has a different orientation. Therefore, the surface normal is different for different incident light rays. Hence, when the individual rays reflect according to the law of reflection, the individual rays scatter in different directions. Furthermore, when either a coherent or a quasi-coherent illumination is applied, high contrast intensity patterns produced by interference among the reflected and the scatter light may be observed in the specular reflected images. The interference effects provide enhanced contrast to the image for navigation.

FIGs. 1a –1c illustrate light reflection from different types of surfaces. FIG. 1a shows reflection of light beam 135 from Lambertian surface 140 into beam pattern 136. A Lambertian surface is a perfectly diffusing surface and the intensity of the light emanating in a given direction from any small surface component is proportional to the cosine of the angle of normal 199 to surface 140. Fig. 1b shows reflection of light beam 145 from specular reflector surface 150 into beam 146 which is at an angle

$\theta_r = \theta_i$, where the angles are defined with respect to surface normal 199. FIG. 1c

shows light beam 155 reflecting from surface 160 into beams 156. Surface 160 is

intermediate in surface characteristics between surface 140 and surface 150 and there

is a specular component as well as a Lambertian component to beam pattern 156.

5   It is important to note that specular reflection is not related to optical speckle.

The images from specular reflection result from imaging the surface to be navigated

over with either coherent or quasi-coherent light. The feature rich images obtained in

accordance with the invention vary markedly across different types of surfaces and

typically have a one to one correlation with the underlying surface. In contrast,

10   speckle images are highly statistical in nature and to a first approximation are not

variable across different types of surfaces. Speckle images exhibit image patterns

where the one-to-one correspondence to visible underlying surface features is limited.

Although speckle is present anytime objects are illuminated by coherent light, the

average size of optical speckle is typically smaller than the pixel size of the imaging

15   array for typical optical navigation applications. When pixel size is appreciably larger

than the mean speckle size, speckle is no longer a reliable pattern for optical

navigation because the multiple bright and dark speckle features incident on a pixel of

the detector array are averaged out over the pixel area. For example, taking an

imaging system with an f number of 10 and a laser source operating at 850 nm results

20   in an average speckle size = 8.5 μm using the formula: *average speckle size* $= f \times \lambda$

where f is the f number and λ is the wavelength. Here, taking a typical detector

array with a pixel size of 60 μm results in more than 49 speckles imaged by each pixel

of the detector array. The resulting averaging removes potentially navigable features

from the speckle distribution.

FIG. 1d is a simplified illustration of scattering from rough surface 105 in accordance with the invention. Incident light rays 110, 115, 120, 125, 130 of an incident light beam each follow the law of reflection resulting in reflected light rays 110', 115', 120', 125', 130' from rough surface 105 and are scattered upon reflection. Light as referred to herein is intended to include electromagnetic radiation over a wavelength range extending from about 1 nanometer (nm) to about 1 millimeter (mm).

FIG. 2 shows a more detailed view of specular reflection from a surface in accordance with the invention. Incident light ray 205 has angular coordinates ϕ_i, θ_i before reflection by surface 220. Typically, surface 220 will have a microscopic roughness or optical irregularity that effects the reflection angle of the reflected light. If reflected light ray 210 lies in the angular cone defined by $\phi_{r_0} \pm \delta\phi_r, \theta_{r_0} \pm \delta\theta_r$, the surface element corresponding to light ray 205 will be captured by the detector.

FIG. 3a is a high level block diagram in accordance with the invention for optical navigation system 300 based on using specular reflection for navigation. Surface 330 is illuminated by light beam 398 from light source unit 304. Specular reflected light beam 399 is reflected from surface 330 to be detected by detector array unit 311 which generates signal 370 that goes to processor 320. Processor 320 provides output signal 375 in response to signal 370. Output signal 375 may be used, for example, to drive the position of a pointer on a computer screen. Processor 320 may be part of optical navigation device 303 or be located elsewhere in optical navigation system 300. In accordance with the invention, some embodiments of optical navigation device 303 may be an optical mouse for a computer system that is hand moveable.

FIG. 3b shows a simplified illustration of components for optical navigation device 303 in accordance with the invention. Light source 305, part of light source unit 304 (see FIG. 3a), is positioned at incident angle θ_i with respect to surface normal 350 and provides light beam 315 incident on lens 301 to produce beam 315'.

5   Lens 301 primarily functions to improve the collection efficiency for beam 315 and lens 301 is optional. Lens 301 may, for example, be a collimating lens. However, beam 315 need not be collimated if, for example, light source 305 is a laser such as a VCSEL or edge emitter. If light source 305 is quasi coherent source such as a narrow band LED (light emitting diode) or LED with a narrow bandwidth filter then lens 301

10   or a limiting aperture may be needed for navigation on smooth surfaces. Use of a limiting aperture reduces the power incident on surface 330 but improves spatial coherence. If lens 301 is used, lens 301 may be a diffractive or a refractive lens or other suitable optical element and may be optically coated to improve performance. Instead of using a narrowing aperture together with a conventional narrowband LED,

15   a narrowband edge emitting LED may be used as the light source.

In the context of this patent, a detector is defined to be a device that converts photons to electrical signals. Detector array 310, part of detector array unit 311 (see FIG. 3a) is positioned at reflection angle θ_r selected such that $\theta_r \approx \theta_i$. Only reflected rays 365 from surface 330 having $\theta_r \approx \theta_i$ make up beam 317 and will be received by

20   detector array 310. The illuminated portion of surface 330 is imaged by lens 307. Point 316 on surface 330 is imaged by lens 307 into point 316' on detector array 310. Hence, the imaging optics allow capture of an image by 310. The image produced by a coherent light source typically includes surface features and interference features. Any speckle present in the image is not important for navigation in

25   accordance with the invention. The interference features arise from coherent addition

of individual rays in the specular reflection field. Imaging lens 307 may be a

diffractive or refractive lens or other suitable optical element to image portions of

surface 330 and may be optically coated with a dielectric thin film to improve

performance. Light source 305 typically is a narrow band laser source such as a

5   VCSEL (vertical cavity surface emitting laser) or an edge emitting laser but may be a

narrow band LED while detector array 310 is typically a CCD, CMOS, GaAs,

amorphous silicon or other suitable detector array. Performance of detector array 310

may be improved by application of anti-reflection dielectric coatings to detector array

310.

10   Having a higher surface contrast and resolution allows optical navigation

device 303 to navigate on smoother surfaces. The effective surface resolution is

defined as the smallest resolvable feature on the navigation surface, such as surface

330. The effective surface resolution depends on the modulation transfer function, the

magnification of the optics and the effective pixel size of the detector array, such as

15   detector array 310. If magnification is fixed, higher surface resolution requires that,

for example, detector array 310 have smaller pixels. The maximum navigation speed

over surface 330 for optical navigation device 303 is limited by the maximum frame

rate of detector array 310 as well as the processing time for the cross-correlation

calculation. The physical displacement of optical navigation device 303 with respect

20   to surface 330 is measured in units of effective pixel size. The effective pixel size is

the image size of the pixel on surface 330. This means that if the pixel size of

detector array 310 of optical navigation device 303 is reduced, the responsivity or

maximum navigation speed of optical navigation device 303 will be reduced.

Typically, tradeoffs between the cost of detector array 310, processor 320, total power

25   consumption and desired responsivity are considered and balanced to arrive at the

surface resolution and optical magnification for embodiments in accordance with the invention.

As optical navigation device 303 moves relative to surface 330, narrow bandwidth scatter patterns are created at different relative positions between optical navigation device 303 and surface 330. Each scatter pattern is created by the specular reflection from surface 330 that is in the field of view of detector array 310. The narrow bandwidth scatter pattern images depend strongly on the wavelength of light source 305. Typically, the wavelength of light source 305 is selected to be at the peak of detector array 310. Because image contrast and signal are typically improved over the prior art shadow pattern optical navigation systems, shorter image integration times are required which allows higher frame rate acquisition to allow navigation at higher velocities.

By comparing successive stored narrow bandwidth specular reflection images in processor 320, the relative motion of optical navigation device 300 with respect to surface 330 can be determined. Correlation of successive narrow bandwidth scatter pattern images is typically used to determine the displacement of the relative movement. Successive captured scatter pattern images partially overlap with one another. Hence, processor 320 identifies features in each scatter pattern image and calculates the displacement and direction of the relative motion. Storing successive scatter pattern images, overlapping features can be identified by processor 320 using standard image correlation algorithms to provide direction and displacement. Further details may be found, for example, in U. S. Patent Number 5,786,804 incorporated herein by reference. In accordance with the invention, relative motion even over very smooth but not optically polished surfaces, such as, for example, glass can be determined.

FIG. 4 is a representation of system 400 in accordance with the invention where optical mouse 425 moves over fixed surface 430. Optical mouse typically includes an detector array unit such as detector array unit 311 of FIG. 3a. A series of specular reflection images is typically converted to positional information in optical

5   mouse 425 by processor 320 (see FIG. 3) and sent by wire or sent wirelessly to central processor unit 475 for display on video screen 470 as a positional pointer such as an arrow. Alternatively, raw or intermediate data may be sent from detector array unit 311 (see FIG. 3a) to central processor unit 475 for processing. Wireless connections may be either radio frequency or infrared and wireless embodiments of optical mouse

10   425 in accordance with the invention may be powered by, for example, a rechargeable battery, fuel cell or solar cells.

FIG. 5 shows an embodiment of optical navigation device 500 in accordance with the invention. Packaged VCSEL and sensor die 510 is discrete and functions as the light source with collimating lens 520 and imaging lens 525 integrated and formed

15   in molded plastic structure 515. Sensor die 535 incorporates an detector array such as detector array 310 discussed above. The integration of collimating lens 520 and imaging lens 525 into molded plastic structure simplifies manufacturing and reduces cost. The detector array in sensor die 535 is positioned to receive light at the angle of reflection θ_r which is equal to the angle of incidence θ_i for beam 595, thereby

20   assuring that the resulting signal from the detector array represents the specular reflection. Sensor die 535 may be oriented so that beam 595 is incident normal to the plane of the detector array.

FIG. 6 shows an embodiment of optical navigation device 600 in accordance with the invention. Integrated VCSEL 610 die functions as the light source with

25   collimating lens 620 and imaging lens 625 integrated and formed in molded plastic

structure 615. Sensor die 635 incorporates an detector array such as detector array 310 discussed above. The integration of collimating lens 620 and imaging lens 625 into molded plastic structure simplifies manufacturing and reduces cost. Beam 695 travels vertically through collimating lens 620 and is reflected by total internal

5   reflection face 675 to be incident on surface 650 at an angle of incidence θ_i. The detector array in sensor die 635 is positioned to receive light at the angle of reflection θ_r which is equal to the angle of incidence θ_i for beam 695, thereby assuring that the resulting signal from the detector array represents the specular reflection. Sensor die 635 may be oriented so that beam 695 is incident normal to the plane of the detector

10   array.

FIG. 7 is a flow diagram showing the steps involved in a method of using optical navigation system 303 in accordance with the invention. In step 701, surface 303 is illuminated by narrow bandwidth light beam 398 at an angle of incidence, θ_i. In step 702, detector array 311 detects reflected narrow bandwidth light beam 399 at

15   an angle of reflection θ_r close to or equal to the angle of incidence θ_i. In step 703, an image signal is generated by detector array 311 in response to narrow bandwidth light beam 399. In step 704, the image signal is processed by processor 320. In step 705, output signal 375 is provided in response to image signal 370 and may be used, for example, to control a positional pointer on video screen 470.

20   While the invention has been described in conjunction with specific embodiments, it is evident to those skilled in the art that many alternatives, modifications, and variations will be apparent in light of the foregoing description. Accordingly, the invention is intended to embrace all other such alternatives, modifications, and variations that fall within the spirit and scope of the appended

25   claims.